

unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DO

AD-A250 204



2

1a. REPORT SECURITY CLASSIFICATION

unclassified

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING

SCHEDULE

4. PERFORMING ORGANIZATION REPORT

NUMBER(S)

3. DISTRIBUTION / AVAILABILITY OF REPORT

unlimited

5. MONITORING ORGANIZATION REPORT NUMBER(S)

AFOSR-TR- 92 0293

6a. NAME OF PERFORMING ORGANIZATION

Stanford University

6b. OFFICE SYMBOL  
(If applicable)

7a. NAME OF MONITORING ORGANIZATION

E &amp; SSS - AFOSR

6c. ADDRESS (City, State, and ZIP Code)

Ginzton Laboratory  
Stanford University  
Stanford, CA 94305-4085

7b. ADDRESS (City, State, and ZIP Code)

Bolling AFB, Building 410  
Washington, DC 203328a. NAME OF FUNDING / SPONSORING  
ORGANIZATION

AFOSR

8b. OFFICE SYMBOL  
(If applicable)

NE

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

F49620-89-C-0001

8c. ADDRESS (City, State, and ZIP Code)

Same as 7b

10. SOURCE OF FUNDING NUMBERS

PROGRAM  
ELEMENT NO.

61102F

PROJECT  
NO.

2306

TASK  
NO.

C1

WORK UNIT  
ACCESSION NO.

11. TITLE (Include Security Classification)

Stanford Center for Research on Superconductivity and Superconductive Electronics

12. PERSONAL AUTHOR(S)

M. R. Beasley

13a. TYPE OF REPORT

final

13b. TIME COVERED

FROM 10-15-88 TO 10-14-91

14. DATE OF REPORT (Year, Month, Day)

92-3-23

15. PAGE COUNT

17

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

superconductivity, superconducting electronics, thin  
film high temperature cuprates

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

New techniques for growing epitaxial thin films of high temperature superconducting cuprates have been developed. The electrical and superconducting properties of the thin films have been investigated by transport, magnetic, optical and tunneling measurements. Insights into the basic nature of the superconducting interaction and the physics of some superconducting devices have been gained.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT

☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION

unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

W. Winstock

22b. TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL

202-767-4933

NE

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.

All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

unclassified

STANFORD CENTER FOR RESEARCH ON  
SUPERCONDUCTIVITY  
AND  
SUPERCONDUCTIVE ELECTRONICS

Final Technical Report

under

Contract F49620-89-C-0001

for the period

15 October 1988 to 14 October 1991

Accession For	
NTIS	CRA&I <input checked="" type="checkbox"/>
DTIC	TAB <input type="checkbox"/>
Unannounced <input type="checkbox"/>	
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U. S. Government.

M. R. Beasley  
Edward L. Ginzton Laboratory  
Stanford University  
Stanford, California 94305



92-13120



92 5 15 091

**STANFORD CENTER FOR RESEARCH ON  
SUPERCONDUCTIVITY  
AND  
SUPERCONDUCTIVE ELECTRONICS**

The impetus for the formation of a Center for research on Superconductivity and superconducting electronics at Stanford was provided by the open ended potential of the newly discovered high Tc copper oxide superconductors for electronic applications. The purpose of the Center was to enhance the ongoing work of the programs of Professors Kapitulnik, Geballe and Beasley in superconductivity and superconducting electronics, including further collaborations with other faculty members at Stanford, with other universities, and with government and industrial laboratories.

The goals envisioned at the start of the center were as follows.

--to determine conclusively the physical mechanism(s) underlying the superconductivity of these new materials, and on the basis of this knowledge to seek improved superconductors, possibly even with higher transition temperatures.

--to develop an understanding of the physical properties of these new superconductors with an eye toward developing generically new, as well as known, superconducting devices; and to produce prototype devices as proofs of principle.

--to synthesize, characterize and optimize thin films and multilayer thin film structures of the new superconductors suitable for physical study and for electronic applications.

--to be prepared to capitalize on any further breakthroughs in new superconducting materials.

--to produce a cadre of young scientists and engineers knowledgeable and experienced in the science and technology of the new superconducting materials.

These goals have been fully achieved in some cases and partly achieved in others as can be seen in the list of accomplishments which are summarized below in sections 2, 3, 4 and 5 and are documented in the publications listed in section 6. Those who have received PhD's or post doctoral support under our program are listed in section 7, along with present location.

## II. Accomplishments in thin film synthesis and processing

(a) We have developed the  $90^\circ$  off axis sputtering process for growing films from composite targets in which the composition of the target is preserved in the films and in which the desired structure is formed directly from the vapor- i.e., *in situ* growth. The *in situ* feature is desirable because no solid state reactions with accompanying changes in volume, morphology, etc., that degrade the quality of the film are involved. This technology has been transferred to a large number of university and industrial laboratories in the United States by the Stanford Center by means of publications, students who have received PhD's and gone on to other organizations, and visitor exchange. The argon-oxygen sputtering pressure is high enough so that the transport through the plasma is mainly diffusive. The mobility of the species at the surface during the growth is critical so that careful control of the surface temperature is required.

(b) We have found, contrary to our own and the expectations of others that the surfaces and the crystal perfection of a-axis films can be superior to c-axis films. The a-axis films grow at lower temperatures, and form better interfaces. A-axis films are thus excellent candidates for making good sandwich-type Josephson junctions, both of the tunneling and proximity effect varieties. There are no twins in the a-axis films but there are lots of grain boundaries, because the in-plane b and c/3 cell lengths are almost the same. In contrast, in the c-axis films, the in-plane a and b axes differ by  $\sim 2\%$ , resulting in heavy twinning.

(c) The relatively good square lattice matching between superconducting YBCO and insulating PrBCO makes it possible to grow superlattices, which as judged by the ion channeling experiments, are as perfect as single crystals of either compound, even though the channeling ions must traverse 20 interfaces. TEM cross sections show the superlattice by an out-of-focus image which is sensitive to the electron density. The in-focus image of the atomic rows shows that the structure maintains itself right through the interfaces. The smoothness of the surface is such that no features can be imaged with our most sensitive SEM (resolution  $\sim 100\text{\AA}$ ). The atomic force microscope shows undulations of  $40\text{\AA}$  over distances thousands of  $\text{\AA}$ . X-ray diffraction scans indicating superlattice satellite peaks also demonstrate high crystalline perfection. The grain boundaries between the b and c in-plane orientations in the a-axis films cause excess resistance. Critical currents for a-axis films are reduced by about two orders of

magnitude from the c-axis films because of these grain boundaries. This should not degrade vertical transport, however, and thus should not be a problem in making sandwich type junctions.

(d) Earlier attempts to produce high quality thin films of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) on Si substrates were thwarted by interface reactions and thermal expansion mismatch. In a collaboration with Xerox several epitaxial buffer layer systems including yttria-stabilized zirconia and MgO which allow the epitaxial growth of YBCO on Si without chemical reaction have been found. All of the materials may be grown in a single process by laser deposition. Pulsed laser deposition has been found to be a rapid and versatile technique for exploring new epitaxial systems on a variety of substrates; this work has provided the first extension of pulsed laser deposition to epitaxy on semiconductor substrates. Although direct epitaxy of YBCO on silicon may not be possible, buffer layers permit the growth of device quality YBCO films with critical current densities in excess of  $10^6 \text{ A/cm}^2$  at 77 K. Methods have been developed to pattern these films in-situ by removing the buffer layer in selected areas to produce isolated superconducting mesas. The complications of thermally induced tensile stress can be avoided through the use of silicon-on-sapphire instead of silicon. This work has revealed methods for controlling the in-plane epitaxy of YBCO films on zirconia via homoepitaxy and nucleation-initiating monolayers. Ongoing research has demonstrated that some of the epitaxial growth processes developed for Si can be adapted to produce similar results on GaAs substrates.

(e) The deposition temperature and pressure for thin films of  $\text{YBa}_2\text{Cu}_3\text{O}_7$  made by different processes have been compared. Several anomalous results are found. For  $\text{O}_2$  pressure  $\leq 10 \text{ mTorr}$ , films with average composition substantially off the 1:2:3 stoichiometry have more bulk-like properties, including higher  $T_c$ 's, compared to films made on-stoichiometry. Films made at lower oxygen pressure also have c -axis lattice constant expanded compared to the films made at higher pressures ( $> 100 \text{ mTorr}$ ). The films show evidence that they are excess hole-doped compared to the ideal material. Altogether, the results strongly suggest that metal-atom point-like defects are quenched into the films. A model based on the presence of Ba-for-Y substitution has been developed and found to be consistent with the experimental results. We suggest that these defects might be a generic property of *in-situ* films.

(f) The  $\text{CuYO}_2$  delafossite-type structure has been identified as a second phase in thin films of Cu- and Y-rich  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (123) made by electron beam co-evaporation at conditions of low oxygen pressure; this phase occurs as extremely small, densely distributed, highly oriented precipitates within the 123 matrix. The smallest (sub-100 Å) [001] oriented precipitates of this hexagonal phase are strained to give a better lattice match to the surrounding 123 structure. The results suggest that, for thin film deposition conditions of sufficiently low temperature and pressure, there may be a tie line between  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  and

CuYO<sub>2</sub> in the equilibrium phase diagram. The size and distribution of the precipitates is such as would be expected to influence structurally sensitive superconducting transport properties, e.g. critical currents.

(g) Highly oriented, high-quality YBCO thin films on MgO substrates were examined and found to have a high density of planar defects such as out-of-phase boundaries and low-angle grain boundaries. The origin of a large number of these boundaries is found to be imperfections in the substrate surface morphology. In addition, it was found that by varying film thickness and film oxygenation temperature, the final twin microstructure could be strongly affected, without any accompanying change in superconducting properties. For extremely high critical current material, twin boundaries do not play a dominant role in determining superconducting properties.

### III. Accomplishments with the MBS Facility

At the present time the favored ways of making thin films of the high T<sub>c</sub> materials is off-axis sputtering (perfected at Stanford) and laser ablation. It is our feeling that if a quantum improvement in the quality of the films is to be made, more powerful approaches must be brought to bear. Toward this end we have been studying an MBE-like approach in which the metallic elements are thermally evaporated in the presence of oxygen. The goal is to achieve MBE-like deposition with all its power and in situ characterization capability.

(a) A program to characterize existing polished substrates for HTSC film growth and then to modify them to improve their smoothness was begun under this program. We have used RHEED and LEED for in situ characterization, and AFM for ex situ examination. Homo-epitaxial growth of electron-beam evaporated MgO and Al<sub>2</sub>O<sub>3</sub> resulted in improved atomic surface ordering compared to polished crystals and similar to that of high temperature annealed crystals, as evidenced by RHEED and LEED patterns. However, AFM scans revealed an array of in-plane ordered rectangular shaped (~ .1mm on a side) mesas (~ 100Å high). We are exploring the effect of growth temperature, surface preparation, and the presence of ion beams during growth on the surface morphology. These preliminary results demonstrate that surface characterization using RHEED and LEED, while indicating good atomic ordering of the surface, does not indicate the true long range smoothness. Published studies by others have used electron diffraction (RHEED and LEED) and x-ray diffraction to claim epitaxial growth and imply surface smoothness. Our results show that additional characterization, such as the AFM, is needed.

(b) We have grown films of the so-called "infinite lattice" copper oxide compound (CuO<sub>2</sub>)<sub>n</sub> (Sr)<sub>n</sub>, using electron beam codeposition of the metals and an atomic oxygen beam from a modified ECR source. The structure was identified

by x-ray diffraction. As expected, these undoped films were insulating, although in some cases self-doping due to Sr vacancies resulted in semiconducting and metallic temperature dependencies of the resistivity. Recent work by others suggests this material can be doped so as to yield a 100K superconductor.

(c) An important, and on-going, aspect of our MBS work has been the development of rate monitoring for the electron beam feed back control that is compatible with the required high oxygen background pressures. We have been using Atomic Absorption (AA) over the past few years, but we are now extending the technology to new elements (Sr and Nd), to lower rates (goal is  $\sim .1$  Å/sec), and to higher accuracies than ever achieved before (the goal is 1%). We are finding that the hollow cathode lamp sources for these elements are not sufficiently stable. With the help of the manufacturer feedback circuits are being developed to stabilize these lamp sources.

(d) A movable mutual inductance probe mounted from the wall of the MBS Loadlock/Process chamber was developed and tested. This has permitted the in situ measurement of the  $T_c$  of a thin film mounted on the recently developed liquid helium cooled substrate fixture. This mutual inductance probe should be ideal for those materials where either contacts on the substrate are not possible or desirable, and where it is not possible to remove the thin film from the vacuum for measurement. Furthermore it will permit in situ complex conductance measurements on 2-D thin film systems.

#### IV. Physical Property Measurements

(a) Using the off-axis sputtering deposition techniques in collaboration with Hewlett-Packard we have carried out a careful, quantitative study of the role of large-angle grain boundaries in the high residual rf losses universally observed in c-axis YBCO thin films on MgO. MgO is a good substrate material for microwave devices because it has a low dielectric constant and is cubic. The latter feature insures that the dielectric properties are isotropic in the plane and makes the design of devices simpler.

(b) The lowest accurate bound on the surface resistance,  $16 \pm 3 \mu\Omega$  at 10 GHz and 4.2K, reported to date has been found for in-situ grown  $YBa_2Cu_3O_7$  thin films. The increase in loss with increasing deviations of the films from the characteristics of ideal, equilibrium single crystals makes clear that values above this level are representative of extrinsic loss mechanisms. Very small quantities of c-axis material misaligned in the surface plane can contribute significant losses. Four percent volume fractions of highly misaligned c-axis grains lead to losses above  $500 \mu\Omega$  at 10GHz and 4.2 K. Our data also show that, for these samples, it is unlikely that the  $16\text{-}\mu\Omega$  value is dominated by loss mechanisms associated with the misaligned material. Losses of a different origin dominate. For the lower-loss films  $R_s$  is correlated to the dc transport characteristics.

(c) We have measured the amount of nonreciprocal circular birefringence of 50 to 800 Å YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> films in transmission with a 15-μm beam diameter. A novel instrument with a sensitivity of 2 μrad for nonreciprocal phase shifts was developed by modifying a fiber-optic gyroscope. It is insensitive to reciprocal phase shifts. We observed no nonreciprocal phase shifts in any samples. This result casts strong doubt upon recent reports that optical nonreciprocal effects were observed in reflection. The latter, if correct would be strong evidence for an exciting theory of the superconductivity of the cuprates, the anyon theory.

(d) We have studied the relation between the magnetic shielding current in epitaxial thin films of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> and the shape of the current-voltage (J-E) characteristic of the superconductor in its critical state. The weak temperature dependence of the relaxation implies a temperature-insensitive J-E characteristic that resembles that of conventional type-II superconductors when a spatial variation of critical current density ( $J_c$ ) is present. We have shown such a distribution of  $J_c$  can be used as an explanation for the apparently large and temperature-insensitive relaxation of the critical states observed in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub>. We also have demonstrated the presence of edge pinning in narrow microbridges of YBaCuO.

(e) We have found a strong substrate dependence of the temperature dependence of the magnetic penetration depth  $\lambda(T)$  at low temperatures. For the best samples the low temperature dependence is exponential, excluding the possibility of nodes in the energy gap in YBCO. Unlike conventional strong-coupled superconductors, however, the inferred temperature dependence of  $\lambda(T)$  is not characterized by a single-gap (scaled, isotropic) BCS temperature dependence. The observed temperature dependence can be fit with either a parallel superconductor model involving the planes and chains or a series weak link model, both with a larger gap of  $2\Delta(0)/k_B T_c = 4.5$ . However, other interpretations are not completely ruled out.

(f) We have used experiments on very thin films to compare and isolate two dimensional effects in the cuprates. By comparing to multilayer systems with similar parameters, we can identify the decoupling of the superconducting planes in magnetic fields at temperatures much above the irreversibility line. These results show that if the irreversibility line is to be considered a melting transition line, it implies melting of the solid state into a liquid of three dimensional flux lines.

(g) Monte Carlo simulations of a model of weakly coupled 2D superconducting planes have been used to identify two melting lines corresponding to the disappearance of the translational and the hexatic order of the vortex lattice in the planes. The Lindemann number corresponding to the translational order-disorder transition is found to be about 0.2 but to deviate from this value in the extreme density limits. We find a significant effect of cutting/reconnection of the vortices on the in-plane stiffness and the mean-square



deviation from equilibrium positions, which should have a profound effect on the dynamics of the system.

(h) We have found that in a-axis superlattices of  $\text{YBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$  the  $\text{CuO}_2$  planes can be divided into alternating 1D-like superconducting/insulating strips. When a magnetic field is applied in the plane of the substrate (perpendicular to the  $\text{CuO}_2$  planes) we find that the resistive transitions of superlattices with modulation wavelengths of  $96\text{\AA}$  ( $48\text{\AA}$ - $\text{YBa}_2\text{Cu}_3\text{O}_7/48\text{\AA}$ - $\text{PrBa}_2\text{Cu}_3\text{O}_7$ ),  $72\text{\AA}$  ( $48\text{\AA}$ - $\text{YBa}_2\text{Cu}_3\text{O}_7/24\text{\AA}$ - $\text{PrBa}_2\text{Cu}_3\text{O}_7$ ), and  $48\text{\AA}$  ( $24\text{\AA}$ - $\text{YBa}_2\text{Cu}_3\text{O}_7/24\text{\AA}$ - $\text{PrBa}_2\text{Cu}_3\text{O}_7$ ) show a crossover with the upper part of the transition insensitive to magnetic fields up to 8T. The crossover temperature is controlled by the PBCO thickness. These results show that in the temperature range where we observe this insensitivity the structure behaves as 1D superconducting-insulating channels whose width is determined by the  $\text{YBa}_2\text{Cu}_3\text{O}_7$  and  $\text{PrBa}_2\text{Cu}_3\text{O}_7$  thicknesses. By comparing these results to those obtained on c-axis superlattices we estimated that  $100\text{\AA}$  a-axis PBCO should produce the complete decoupling of the YBCO channels. The channel dimensions and the perfection of the superlattices are such that the study of quasi 1-D transport is feasible.

(i) Extensive theoretical studies of the "chiral spin liquid" state, which is the starting point for calculations of high- $T_c$  superconductors based on the anyon pairing idea, have been carried out. This has led to the development of a gauge theory formalism that has made realistic calculations possible for the first time. The optical conductivity of the t-J model, thought by many theorists to be an appropriate idealization of the high- $T_c$  problem, has been calculated using this formalism, and shown to agree well with both exact cluster calculations of the model and the mid-infrared conductivity seen in real high- $T_c$  materials. Through this work the way has been opened which should permit calculation of accessible experimental quantities, such as the photoemission spectrum, the a.c. spin susceptibility, pairing susceptibility, and the energy gap.

## V. Device Physics Studies

(a) We have investigated the anisotropy of the Josephson proximity coupling of conventional low  $T_c$  superconductors to YBCO thin films. Devices that couple to YBCO along the c-axis and along the a-axis have been prepared and their properties compared. The superconducting coherence length is very different along these two directions, the a-axis coherence length being much longer than that along the c-axis. The results show Josephson proximity coupling to a low temperature superconductor (Pb) can be achieved on an a-axis film but not on a c-axis film, despite the fact that a state-of-the-art low contact resistance was achieved.

(b) Studies of the proximity coupling of a-axis  $\text{YBa}_2\text{Cu}_3\text{O}_7$  through Ag to a BCS superconductor have shown that the  $I_c R$  product is systematically much smaller than the BCS limit of  $\sim 5\text{mV}$ . The observed  $I_c R$  values range from 10 to  $100\ \mu\text{V}$  in the  $\text{YBa}_2\text{Cu}_3\text{O}_7$  a-direction to apparently zero in the c-direction. The reduced  $I_c R$  in the a-direction can be understood as arising from a large boundary resistance, consistent with the mismatch of carrier densities across the  $\text{YBa}_2\text{Cu}_3\text{O}_7$ -Ag interface. However, the same analysis gives an  $I_c R$  in the c-oriented junctions that is at least three orders of magnitude larger than observed.

VI. List of publications in which the research was fully or partially supported by the Center in the form of stipends, and/or research expenditures, and/or facilities.

- "Analogy between  $\text{Y}_2\text{Ba}_4\text{Cu}_8\text{O}_{16-x}$  and  $\text{Bi}_4\text{Ca}_2\text{Cu}_4\text{O}_{16+x}$ ," by K. Char, R. W. Barton, A. F. Marshall, A. Kapitulnik and S. Laderman, *Physica C* 152, 475 (1988).
- "Preparation of Oriented Bi-Ca-Sr-Cu-O Thin Films Using Pulsed Laser Deposition," by D. K. Fork, F. A. Ponce, R. I. Johnson, J. B. Boyce, G. B. Anderson, G. A. N. Connell, C. B. Eom and T. H. Geballe, *Applied Physics Letters* 53 (4), 337-339.
- "Photoemission Study of the Surface Chemistry and the Electronic Structure of Copper Oxide Superconducting Thin Films," by Z.-X. Shen, J. J. Yeh, I. Lindau, W. E. Spicer, J. Z. Sun, K. Char, N. Missert, A. Kapitulnik, T. H. Geballe and M. R. Beasley, *SPIE Vol. 948 - High-Tc Superconductivity: Thin Films and Devices* (1988); pp. 41-48.
- "Molecular Beam Epitaxy of Layered DY-BA-CU-O Compounds," D. G. Schlom, J. N. Eckstein, E. S. Hellman, S. K. Streiffer, J. S. Harris, Jr., M. R. Beasley, J. C. Bravman, T. H. Geballe, C. Webb, K. von Dessonneck and F. Turner, in *Extended Abstracts, High Temperature Superconductors II*, W. H. Butler, B. Batlogg and C. W. Chu, eds. (Materials Research Society, Pittsburgh, 1988) p. 197.
- "Electronic Structure of Ceramics and Thin Film Samples of High-Tc  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$  Superconductors: Effects of Ar<sup>+</sup> Sputtering, Oxygen Exposure and Rb Deposition," P.A.P. Lindberg, P. Soukiassian, Z.-X. Shen, S. I. Shah, C. B. Eom, I. Lindau, W. E. Spicer, and T. H. Geballe. *Appl. Phys. Lett.* 53(20), 14 November 1988, pp.1970-1972.
- "Properties of  $\text{Y}_2\text{Ba}_4\text{Cu}_8\text{O}_{20-x}$  Thin Films," by A. Kapitulnik and K. Char, *International Journal of Modern Physics B*, vol. 1, no. 5 (1988) 1267-72.
- "Raman Scattering Spectra of Superconducting  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  Single Crystals," D. Kirillov, I. Bozovic, T. H. Geballe, A. Kapitulnik, and D. B. Mitzi., *Physical Review B* 38 (16), 1 December 1988, pp. 11955-11957.

- "Advances in the Fabrication of High-Temperature Superconductors," by M. R. Beasley, Physics News in 1988, Physics Today, pp. 23-25, January 1989.
- "Nature of the States Near the Fermi Level of the Layered Superconductors of  $\text{Bi}_2\text{Ca}_1\text{Sr}_2\text{Cu}_2\text{O}_8$  and  $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ ," Z.-X. Shen, P.A.P. Lindberg, P. Soukiassian, C. B. Eom, I. Lindau, W.E. Spicer, and T. H. Geballe, Physical Review B 39 (1) 1 Jan 1989.
- "Power Law Temperature Dependence of the Electrodynamical Properties in Oriented  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  and  $\text{Y}_2\text{Ba}_4\text{Cu}_8\text{O}_{16-d}$  Films," by Lawrence Drabek, John P. Carini, and George Gruner (UCLA); T. Hylton, K. Char and M. R. Beasley (Stanford), Phys. Rev. B 39, 785-788 (January 1, 1989).
- "Systematic Effects in Thin Film Tunnel Junctions of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$ ," by Mark Lee, M. Naito, A. Kapitulnik and M. R. Beasley, Solid State Comm. 17, No. 4, 449-452 (April 1989).
- "Low Frequency Resistance Fluctuations in Films of High Temperature Superconductors," by P. Rosenthal, R. H. Hammond and M. R. Beasley (Stanford), R. Leoni, P. Lerch and J. Clarke (U. C. Berkeley), IEEE Trans. on Magnt. MAG-25, 973-975, March 1989.
- "Flux Noise and Flux Creep in YBCO Thin Films," by M. J. Ferrari, M. Johnson, F. C. Wellstood, J. Clarke (U. C. Berkeley and Lawrence Berkeley Lab), P. Rosenthal, R. Hammond, M. R. Beasley (Stanford), IEEE Trans on Magnt. MAG-25, 806-809, March 1989.
- "Surface Impedance Studies of the High-Tc Oxide Superconductors," by T. L. Hylton, M. R. Beasley, A. Kapitulnik (Stanford), J. P. Carini, L. Drabek, G. Gruner, (UCLA), IEEE Trans. on Magnt. MAG-25, 810-813, March 1989.
- "Phase Characterization of Dysprosium Barium Copper Oxide Thin Films Grown on Strontium Titanate by Molecular Beam Epitaxy," E. S. Hellman, D. G. Schlom, A. F. Marshall, S. K. Streiffer, J. S. Harris, Jr., M. R. Beasley, J. C. Bravman, & T. H. Geballe, J. Mater. Res., vol. 4, No. 3, May/June 1989.
- "Measurements on Thin-Film High-Tc Superconductors," by A. Kapitulnik and K. Char, Journal of Research and Development. 33 (3) May 1989.

- "Orthorhombic Distortion and Cation Ordering in  $\text{Y}_2\text{Ba}_4\text{Cu}_8\text{O}_{16}$  and  $\text{Er}_2\text{Ba}_4\text{Cu}_8\text{O}_{16}$  High  $T_c$  Thin Films,"** by S. S. Laderman, (Hewlett Packard), K. Char, Mark Lee, M. Hahn, R. H. Hammond, M. R. Beasley, T. H. Geballe, A. Kapitulnik (Stanford), and R. Barton (Conductus), *Phys. Rev. B* 39 pp. 11648-52 (June 1, 1989).
- "Tunneling and the Energy Gap in the High-Temperature Superconductors,"** by Mark Lee, A. Kapitulnik and M. R. Beasley, in *Mechanisms of High Temperature Superconductivity*, eds. Kamimura and Oshiyama (Springer-Verlag, Berlin, 1989), pp. 220-228.
- "The Origin of the Superstructure in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$  as Revealed by Scanning Tunneling Microscopy,"** M.D. Kirk, J. Nogami, A.A. Baski, D.B. Mitzi, A. Kapitulnik, T. H. Geballe, C.F. Quate, *Science*, 242, 1673-1675 (23 December 1988).
- "Magnetic Flux Motion and Its Influence on transport Properties of the High- $T_c$  Oxide Superconductors,"** J. Z. Sun, K. Char, M. R. Hahn, T. H. Geballe, and A. Kapitulnik, *Appl. Phys. Lett.* 54(7), 13 February 1989.
- "Measurements of the Magnetic Penetration Depth in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Thin Films by the Microstrip Resonator Technique,"** by Steven M. Anlage, Hsuan Sze, Howard J. Snortland, Shuichi Tahara, Brian Langley, Chang-Beom Eom, M. R. Beasley and Robert Taber, *Appl. Phys. Lett.* 54, pp. 2710-12, June 26, 1989.
- "Critical Current Behavior in Narrow  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Thin Films,"** by Shuichi Tahara, S. M. Anlage, Chang-Beom Eom, D. K. Fork, T. H. Geballe and M. R. Beasley, in *Proceedings of International Conference on Materials and Mechanisms of Superconductivity: High Temperature Superconductors II*, eds. R. N. Shelton, W. A. Harrison and N. E. Phillips (North-Holland, 1989), pp. 1175-76.
- "Magnetic Penetration Depth Measurements in Low and High  $T_c$  Thin Film Superconductors at Microwave Frequencies,"** by S. M. Anlage, B. Langley, J. Halbritter, S. Tahara, H. Sze, N. Switz, C.-B. Eom, H. J. Snortland, R. Taber, T. H. Geballe and M. R. Beasley, in *Proceedings of International Conference on Materials and Mechanisms of Superconductivity: High Temperature Superconductors II*, eds. R. N. Shelton, W. A. Harrison and N. E. Phillips (North-Holland, 1989), pp. 1645-46.

- "In situ Grown  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Thin Films From Single Target Magnetron Sputtering," C.B. Eom, J.Z. Sun, K.Y. Yamamoto, A.F. Marshall, K.E. Luther, and T.H. Geballe, Appl. Phys. Lett. 55(6), 7 August 1989.
- "High Temperature Superconductive Thin Films," by M. R. Beasley, (invited), IEEE Proceedings 77, pp. 1155-63 (August 1989).
- "Vortex Motion and Time Dependent Magnetic Responses in High  $T_c$  Superconductors," J. Z. Sun, C.B. Eom, B. Lairson, J.C. Bravman, T.H. Geballe and A. Kapitulnik, Physica C 162-164, (1989) 687-688.
- "Properties of the chiral-spin-liquid state," by R. B. Laughlin and Z. Zou, Physical Review B 41, No. 1, 664-687, January 1, 1989.
- "Charged excitations of the chiral spin liquid," by Z. Zou and R. B. Laughlin, Physical Review B 42, No. 7, 4073-79, September 1, 1990.
- "Elimination of Current Dissipation in High Transition Temperature Superconductors," J.Z. Sun, B. Lairson, C.B. Eom, J. Bravman and T.H. Geballe, SCIENCE, Jan. 19, 1990, Vol 247, pp. 307-309.
- "Distribution of Flux Pinning Energies in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  and  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$  from Flux Noise," by M. J. Ferrari, Mark Johnson, Frederick C. Wellstood and John Clarke (Berkeley), D. Mitzi, P. A. Rosenthal, C.-B. Eom, T. H. Geballe, A. Kapitulnik and M. R. Beasley (Stanford), Phys. Rev. Lett. 64, pp. 72-75, January 1, 1990.
- "Resistive Loss at 10 GHz in c-Axis Aligned in situ Grown  $\text{YBa}_2\text{Cu}_3\text{O}_7$  Films," S.S. Laderman, R.C. Taber, R.D. Jacowitz, J.L. Moll, C.B. Eom, T.L. Hylton, A.F. Marshall, T.H. Geballe and M.R. Beasley, Physical Review B 43(4) 1 February 1991.
- "A Test for Non-Reciprocal Circular Birefringence in  $\text{YBa}_2\text{Cu}_3\text{O}_7$  Thin Films," S. Spielman, K. Fesler, C.B. Eom, T.H. Geballe, M.M. Fejer and A. Kapitulnik, Physical Review Letters 65(1), 123-126.
- "Anisotropic Proximity Coupling in small  $\text{YBa}_2\text{Cu}_3\text{O}_7$  -normal-Pb Junctions," M. Lee, D. Lew, C.B. Eom, T.H. Geballe, and M.R. Beasley, Appl. Phys. Lett. 57(11), 10 September 1990..

- "Critical Currents, Pinning and Edge Barriers in Narrow  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Thin Films," S. Tahara, S.M. Anlage, J. Halbritter, C.-B. Eom, D.K. Fork, T.H. Geballe and M.R. Beasley, Physical Review B **41** (16) 1 June 1990.
- "Synthesis and Properties of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  Thin Films Grown *in-situ* by  $90^\circ$  Off-Axis Single Magnetron Sputtering," C.B. Eom, J.Z. Sun, S.K. Streiffer, A.F. Marshall, B.M. Lairson, K. Yamamoto, S.M. Anlage, J.C. Bravman, T.H. Geballe, *Physica C* **171** (1990) 354-382.
- "Breakdown Field in Highly Anisotropic Superconductors," by G. Deutscher and A. Kapitulnik, *Physica A* **168** (1990) 338-344.
- "Flux Motion in a Two-Dimensional Single Crystal Nb Film," by J. W. P. Hsu and A. Kapitulnik, *Appl. Phys. Lett.* **57** (10) 9-3-90, 1061-63.
- "Correlation Between Insitu Growth Conditions and Thermodynamic Stability Criteria for  $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_y$ ," by R. H. Hammond, V. Matijasevic and R. Bormann, *Science and Technology of Thin Film Superconductors 2*, Edited by R. D. McConnell and R. Noufi, Plenum Press, New York, 1990, pages 395-401.
- "Microstructure of Cu and Y Rich  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  Thin Films: Identification of the  $\text{CuO}_2$  Phase," by A. F. Marshall, V. Matijasevic, P. Rosenthal, K. Shinohara, R. H. Hammond and M. R. Beasley, *Appl. Phys. Lett.* **57** (11) Sept. 90, 1158-60.
- "Epitaxial and Smooth Films of a-axis  $\text{YBa}_2\text{Cu}_3\text{O}_7$ ," C.B. Eom, A.F. Marshall, S.S. Laderman, R.D. Jacowitz and T.H. Geballe, *Science*, **B**. 249, Sept. 28, 1990, pp. 1549-1552.
- "Temperature Dependence of the Magnetic Penetration Depth in Nb, NbCN and  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Thin Films," S.M. Anlage, B.W. Langley, G. Deutscher, R.W. Simon, C.B. Eom, M.R. Beasley and T.H. Geballe, published in the proceedings of the LT-19 Satellite Conference on High Temperature Superconductivity, (13-15 August 1990, Queens' College, Cambridge).
- "Measurement of Quasi-Particle Lifetimes in a Superconductor from Kinetic Inductance," M. Johnson, M.R. Beasley, T.H. Geballe, N. Bluzer, S.R. Greenfield, J.J. Stankus, M.D. Fayer.

"Anomalous Photoresponse of Metal Films," M. Johnson, M.R. Beasley, T.H. Geballe, S. R. Greenfield, J. J. Stankus, and M. D. Fayer, *Applied Physics Letters* 58 (6), 568-570.

"A-axis oriented  $\text{YBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$  superlattices," C.B. Eom, A.F. Marshall, J.-M. Triscone, B. Wilkens, S.S. Laderman and T.H. Geballe, *Science*, v. 251, 15 February 1991, pp. 780-783.

"Superconducting Transition Temperature in a  $\text{Nb}/\text{Nb}_x\text{Si}_{1-x}$  Bilayer System," by Julia W. P. Hsu, Sung I. Park, G. Deutscher and Aharon Kapitulnik, *Phys. Rev. B* 43 (4) February 1, 1991.

"A Search for a Proximity Effect Induced Gap in Gold/High  $T_c$  Junctions," D.S. Dessau, B.O. Wells, Z.-X. Shen, W.E. Spicer, A.J. Arko, R.S. List, C.G. Olson, C.B. Eom, D.B. Mitzi, A. Kapitulnik and T.H. Geballe, *Applied Physics Letters* 58 (12), 1332-1334.

"Orientation dependent resistive transition broadening in magnetic field of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  thin films," C. -B. Eom, J. Z. Sun, S. Ryu, S. S. Laderman, K. Yamamoto, A. Kaptiulnik and T. H. Geballe, *Physica C* 162-164 (1989) 605-606 (1989).

"In situ growth of superconducting  $\text{YBaCuO}$  using reactive electron-beam coevaporation," N. Missert, R. Hammond, J. E. Mooij, V. Matijasevic, P. Rosental, T. H. Geballe, A. Kapitulnik, M. R. Beasley, S. S. Laderman, C. Lu, E. Garwin, R. Barton, *IEEE Transactions on Magnetics* 25 (2) 2418-2421 (1989).

"The Growth Mechanisms and Anisotropic Transport Properties of (103) Oriented  $\text{YBa}_2\text{Cu}_3\text{O}_7$  Thin Films," C. B. Eom, A. F. Marshall, Y. Suzuki, B. Boyer, R. F. W. Pease and T. H. Geballe. *Nature* 353 344 (1991).

"Magnetic Relaxation, Current-Voltage Characteristics, and Possible Dissipation Mechanisms for High  $T_c$  Superconducting Thin Films of Y-Ba-Cu-O," by J. Z. Sun, C. B. Eom, B. Lairson, J. C. Bravman and T. H. Geballe, *Physical Review B* 43, 4, 2-1-91, 3002-08.

"Measurements of the Temperature Dependence of the Magnetic Penetration Depth in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Superconducting Thin Films," by S. M. Anlage, B. Langley, G. Deutscher, Jurgen Halbritter and M. R. Beasley, *Phys. Rev. B* 44, 17 November 1, 1991, pages 9764-67.



"Interface Resistance and Reduction of IcR product in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>-Ag-Pb Proximity Junctions," by Mark Lee and M. R. Beasley, Applied Physics Letters 59 (5) July 29, 1991 pages 591-593.

"Anisotropy of Low Energy Electronic Raman Scattering in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>," by D. Kirillov, C. B. Eom and T. H. Geballe, Physical Review B 43, 4, 2-1-91, 3752-55.

"Correlation Between the In Situ Growth Conditions of YBCO Thin Films and the Thermodynamic Stability Criteria," by R. H. Hammond and R. Bormann, Physica C 162-164 (1989) 703-704, North Holland.

"Evidence for Cation Disorder in In-Situ Grown YBaCuO Superconducting Films," by V. C. Matijasevic, R. H. Hammond, P. Rosenthal, K. Shinohara, A. F. Marshall, M. R. Beasley and R. Feenstra, E-MRS, Strasbourg, May 27-31, 1991.

"Dynamics of the Vortex State in High Temperature Superconductors," by A. Kapitulnik, for the Los Alamos Symposium, "Phenomenology and Applications of High Temperature Superconductors," August, 1991.

"Monte Carlo Simulation of Flux Lattice Melting in a Model High T<sub>c</sub> Superconductor," by S. Ryu, S. Doniach, G. Deutscher and A. Kapitulnik.

"In situ Synthesis on YBaCuO Thin Films by Electron Beam Coevaporation," by Kazuhiko Shinohara, Vladimir Matijasevic, Peter A. Rosenthal, Robert H. Hammond and M. R. Beasley, in High Temperature Superconductors, ed. P. Vincenzini (Elsevier Science Publishers, 1991), pp. 841-849.

## VII. Those who have received PhD's or post doctoral support

### Graduates:

Kookrin Char	Conductus
Julia W. P. Hsu	AT&T Bell Labs
C.-B. Eom	AT&T Bell Labs
V. Matijasevic	Delft University
P. Rosenthal	NIST
T. Hylton	IBM
J. Z. Sun	IBM
Mark Lee	NEC Princeton

**Post Docs:**

**J.-M. Triscone**

**S. M. Anlage**

**Z. Zou**

**University of Geneva**

**University of Maryland**

**Princeton Institute for Advances Studies**